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Article

A Typology of Virtual Reality Locomotion Techniques

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Abstract: Researchers have proposed a wide range of categorization schemes in order to characterize the space of VR locomotion techniques. In a previous work, a typology of VR locomotion techniques was proposed, introducing motion-based, roomscale-based, controller-based, and teleportation-based types of VR locomotion. The fact that (i) the proposed typology is used widely and makes a significant research impact in the field and (ii) the VR locomotion field is a considerably active research field, creates the need for this typology to be up-to-date and valid. Therefore, the present study builds on this previous work, and the typology's consistency is investigated through a systematic literature review. Altogether, 42 articles were included in this literature review, eliciting 80 instances of 10 VR locomotion techniques. The results indicated that current typology cannot cover teleportation-based techniques enabled by motion (e.g., gestures and gazes). Therefore, the typology was updated, and a new type was added: "motion-based teleporting."

Keywords: human-computer interaction; literature review; typology; virtual reality; VR locomotion

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1. Introduction

After the major hardware-driven revival that virtual reality (VR) has undergone over the past decade, the VR locomotion field, i.e., the domain about the ability to navigate in VR environments, has gained much research interest. During the past few years, various locomotion techniques have been developed and proposed to accommodate system capabilities, task demands, and user preferences [1,2]. However, the fact that these techniques must be tailored to each specific use context renders the search for new and better locomotion techniques far from over [1,2]. To characterize the space of VR locomotion possibilities, researchers have proposed various categorization schemes [1] that use different terms–e.g., metaphors, taxonomies, attributions, and typologies–offering a structure that clusters similar techniques and provides a high-level view that can help researchers and practitioners in this field quickly identify whole groups of locomotion techniques [1,2]. For example, the work of Prinz et al. [2] provides an extensive overview of the taxonomies and categorizations of locomotion techniques over time (1994 to 2020), as well as examines their common elements and the research impact that they have made.

In a previous work, a typology of VR locomotion techniques was proposed (Figure 1) based on an analysis of a systematic literature review's results [3]. The review analyzed the VR locomotion techniques that have been studied from 2014–2017, their interaction-related characteristics, and the research topics addressed in these studies [3]. Altogether, 36 articles were included in that literature review, which elicited 73 instances of 11 VR locomotion techniques, e.g., real-walking, walking-in-place, point and teleport, joystick-based locomotion et al. [3].

The literature review's results [3] allowed for classification of VR locomotion techniques, and the documentation of the techniques' interaction aspects led to the development of the classification categories, i.e., *interaction type*, *VR motion type*, and *VR interaction space* [3]. *Interaction type* "describes the way in which the user triggers VR navigation" [3]. Therefore, locomotion can be *physical*, i.e., "exploiting physical motion cues for navigation and translating natural movement to VR motion through some kind of body tracking," or it can be *artificial*, i.e., "utilizing input devices to direct VR motion and navigation [4]" [3]. *VR motion type* "assesses the nature of the user's motions in the VR environment" [3] and can be *continuous*, "supporting smooth, uninterrupted movement in the virtual environment," or *non-continuous* "providing instantaneous, non-continuous movement transitions [5]" [3]. Finally, VR locomotion techniques may operate in an *open VR interaction space*, "supporting navigation in a virtual environment that surpasses the limits of the real environment," or they can offer *limited* interaction space "due to the limitations that the physical environment places on the size of the virtual one [6]" [3].

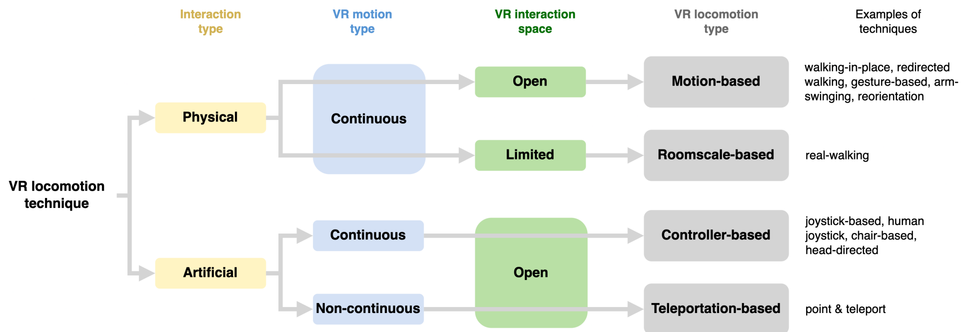

Figure 1. The VR locomotion typology, as presented in [3].

Consequently, based on [3], the documented VR locomotion techniques were assigned to the classification categories, creating four distinct VR locomotion types (visualized in Figure 1):

- **Motion-based**:"The VR locomotion techniques under this type utilize some kind of physical movement to enable interaction, while supporting continuous motion in open VR spaces. This VR locomotion type includes such techniques as walking-in-place, redirected walking, arm swinging, gesture-based locomotion and reorientation" [3].
- **Room scale-based**: "This VR locomotion type utilizes physical movement to enable interaction, and it supports continuous motion (as with the motion-based type); however, the interaction takes place in VR environments whose size is limited by the real environment's size. ... The real-walking locomotion technique falls under this type" [3].
- **Controller-based**: "For this VR locomotion type, controllers are utilized to move the user artificially in the VR environment. The VR interaction space is open, and the motion is continuous. This type includes such techniques as joystick-based, human joystick, chair-based and head-directed locomotion" [3].
- **Teleportation-based**: "The VR locomotion techniques under this type utilize artificial interactions in open VR spaces with non-continuous movement, as the user's virtual viewpoint is instantaneously teleported to a predefined position by utilising visual 'jumps'. Point and teleport is a VR locomotion technique that falls under this type" [3].

When discussing these type's typology and characteristics, Boletsis [3] stated: "*Motion-based* locomotion differs from *room scale-based* in terms of their *VR interaction space*, while *controller-based* locomotion differs from *teleportation-based* in terms of their *VR motion type*. *Motion-based* and *room scale-based* locomotion differ from *controller-based* and *teleportation-based* locomotion in terms of their *interaction type*. Furthermore, the analysis of the reviewed VR locomotion techniques showed that techniques with *physical* interaction presented solely *continuous* VR motion, while artificial techniques were exclusively facilitating navigation in *open*, unlimited VR environments."

The proposed typology of Boletsis [3] was created to be "a useful tool for researchers and users who want to present and describe the features of a VR locomotion technique utilizing a standardized description that clearly distinguishes one technique from another" [3]. Simultaneously, the types were constructed to "serve as a common ground for researchers of Human-Computer Interaction and VR and the public who uses these systems to communicate the interaction aspects and functionalities that were previously difficult to describe and classify, thus enhancing the field's social impact" [3].

Up until now, the work of Boletsis [3] with the proposed typology has been reported by Prinz et al. [2] as one of the publications with the greatest impact on the VR locomotion research field based on citations per year metrics. The typology so far has been utilized in several works to describe VR locomotion techniques' characteristics and interaction elements in areas such as video games [7] and commercial social VR platforms [8]. Moreover, it has been used in several comparative studies to justify the selection of certain VR locomotion techniques [9–13]. The fact that (i) the proposed typology of [3] is used widely [7–13] and is considered to have a significant research impact in the field [2] and (ii) the VR locomotion field is a considerably active research field [1,2], creates the need for this typology to be up-to-date and valid.

This work builds on Boletsis [3] and its future-work direction (Section 5 of [3]). The proposed typology therein was presented as a preliminary classification scheme for researchers, users, and developers of the field. The aim of this work is to take the typology to the next maturity level, evaluating it and, ultimately, making it more relevant to the latest developments in the VR locomotion field, so that it can keep being a useful tool for its target group. To do so, the typology's consistency and contemporary value is investigated by examining how the VR locomotion techniques presented in the 2021 research fit into the proposed typology of [3] and whether new VR locomotion types need to be created and/or whether existing ones should be adjusted. To document the VR locomotion techniques of 2021 and their characteristics, a systematic literature review is conducted.

This paper is organized as follows. The literature review methodology is described in Section 2, and the review is presented in Table 1. The findings from the review process are presented in Section 3, and a discussion of the key findings and study limitations is presented in Section 4. The paper concludes in Section 5.

2. Methodology

This study conducts a theoretically grounded evaluation of the proposed typology of Boletsis [3] based on a systematic review of the existing VR locomotion literature. The systematic literature review aims to document VR locomotion techniques and assess whether they fit under the proposed typology, thereby investigating the typology's consistency.

In the base article (cf. [3]), a literature review was implemented in an explorative way to map out the VR locomotion field and its interaction aspects, and the proposed typology of VR locomotion techniques was a product of the review. In this article, the typology is prioritized, i.e., it is the subject of the main research question, and the literature review is used as a more focused methodological means to examine the typology's consistency. Consequently, the literature review's role herein is to supplement, but not lead, this article's narrative.

The literature review uses the same methodology as that used in [3], so that methodological consistency – and, thus, comparability of results between the two studies – is achieved. Replication of the methodology in [3] can ensure that the results regarding the typology and VR locomotion's current state-of-the-art are solely a product of a valid comparison between VR locomotion techniques from different time periods, and that these results are not skewed, nor affected by some methodological differences between studies.

Therefore, this literature review also has been undertaken as a systematic literature review based on the original guidelines as proposed by Kitchenham [14], which align with the PRISMA guidelines [15], though they are specific to software engineering and can be viewed as more focused for purposes of the topic examined herein [16,17]. A review protocol based on the Kitchenham guidelines, the PRISMA-P checklist [18], and the methodology of Boletsis [3] was developed before the review was conducted and has been used as a guide to conduct the review. The review protocol can be retrieved at https://boletsis.net/mti2022/review-protocol.pdf (accessed on 17 August 2022). The review's methodology is described fully hereafter for improved readability purposes, even though parts of the methodology used in [3] are replicated and repeated.

Finally, the literature review focuses on recently studied VR locomotion techniques, with the latest technical VR advances included in the studied VR locomotion techniques, thereby assessing the contemporary value of the investigated VR locomotion typology effectively. The year 2021 was chosen as the time period for documenting the recently studied VR locomotion techniques based on pilot literature searches (see also Section 2.2).

2.1. Research Questions

To assess the typology's consistency, a main research question (MRQ) and two research subquestions (RQ1 and RQ2) are formulated and investigated:

- **MRQ:** To what degree can recently studied VR locomotion techniques be classified under the proposed VR locomotion typology of Boletsis [3]?
- **RQ1:** Which VR locomotion techniques have been studied recently?
- **RQ2:** What are the interaction-related characteristics of the recently studied VR locomotion techniques?

2.2. Search Strategy

As in [3], a systematic search of the literature was performed in the Scopus academic search engine, which searches through the ACM and IEEE databases, along with other publishers' databases, e.g., Elsevier, Springer, Taylor & Francis, Sage, Emerald, Oxford University Press, Cambridge University Press et al. Apart from the wide coverage of the examined field, Scopus also was chosen due to its flexible result-filtering capabilities [3,19,20].

To define an appropriate study sample size for evaluating the typology and further define the search period, i.e., the temporal element of the RQs expressed by "recently", the Kitchenham guidelines were followed. Based on those, pilot literature searches were conducted using the keywords from Boletsis [3] and starting from the latest complete publication year when the search took place (2022), i.e., 2021, going backward. The sample size of Boletsis [3] that produced the proposed typology defined the threshold for the targeted sample size. The pilot search in 2021 alone provided strong indications that the necessary sample size for assessing the typology could be acquired and, therefore, this year was included in the search query.

The publications' abstracts were utilized to retrieve relevant articles, utilizing the following Scopus database advanced-search query string:

> *ABS (("locomotion" OR "navigation technique") AND ("empirical" OR "studied" OR "study" OR "evaluation" OR "evaluate" OR "examination" OR "examine") AND ("virtual reality" OR "virtual environment" OR "virtual world")) AND (LIMIT-TO (PUBYEAR, 2021))*

Finally, applicable articles also were identified through backward reference searching [21]. Scopus, Google Scholar, and Web of Science were utilized for this purpose to run general searches of specific references and to identify relevant articles [3].

2.3. Inclusion and Exclusion Criteria

The inclusion and exclusion criteria described in [3] also were used in this review. Peer-reviewed articles published between January 2021 and December 2021 with the following characteristics were included:

- those written in English,
- those that included at least one VR locomotion technique,
- those that included a user study that examined direct or indirect aspects of the VR locomotion technique(s),
- those that included a fully immersive VR setup utilizing head-mounted displays (HMDs) [3].

The peer-review process adds to the publications' credibility and reliability [3]. The conduct of user studies evaluating VR locomotion techniques ensures that these techniques exist, are usable, and operate beyond the conceptual level [3]. HMD-based, fully-immersive VR was included so that the technology used for the techniques' development is up-to-date and relevant for researchers , as well as regular users, who now have access to low-to-medium-cost HMD systems [3].

Consequently, articles with the following characteristics were excluded:

- those that utilized solely projection-based, desktop-based, or tablet-based virtual environments,
- those that addressed solely conceptual VR locomotion topics (theoretical models, frameworks, literature reviews et al.),
- those that did not include an empirical, user study,
- those that utilized VR locomotion techniques as a technological/research tool for studying an unrelated topic [3].

2.4. Screening Process and Results

Figure 2 visualizes the screening process and its results. The full list of articles can be retrieved at https://boletsis.net/mti2022/scopusresults-2021.pdf (accessed on 17 August 2022). The screening process was based on the articles' full text, and both authors screened the articles at every step in the process. Ultimately, 42 articles were included in the review, and both authors reviewed all articles independently. The two authors/reviewers conjointly shaped the review's categories based on the data-extraction process and the previously formed categories of Boletsis [3]. The review's final validation exercise demonstrated a high level of agreement between the authors/reviewers (>80%), and any disagreements were discussed and settled.

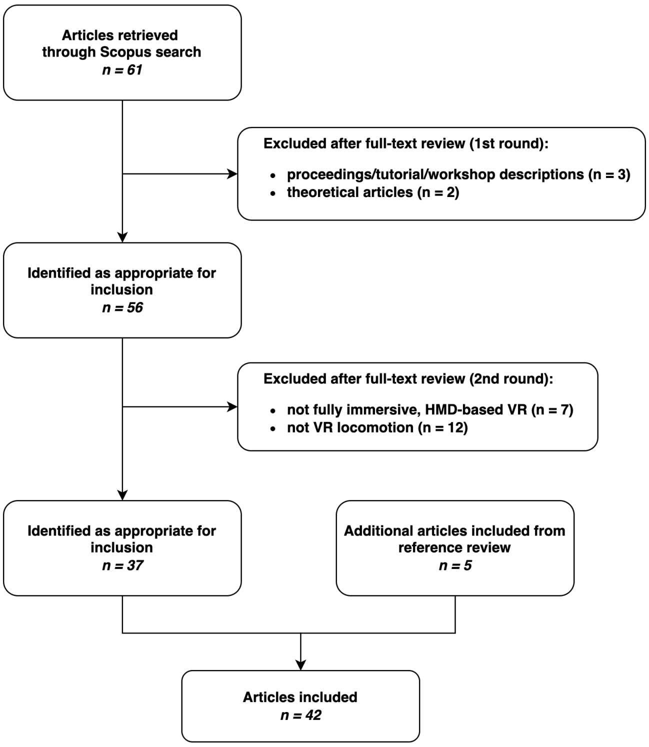

Figure 2. Flowchart of included/excluded articles.

2.5. Data Collection

The screening process elicited 42 articles that satisfied the inclusion criteria. As in [3], the data extracted from each article included:

- the full reference,

- the description and title of the VR locomotion technique(s),
- the interaction aspects of the VR locomotion technique(s) (e.g., interaction type, movement type, VR interaction space, devices).

If data were missing, the study's authors were contacted. The two authors/reviewers conjointly performed the data-extraction process.

2.6. Data Analysis

Identification of the VR locomotion techniques and their interaction aspects was based on the descriptions that the articles provided, as cross-checked with other related or reviewed publications in the field, to establish their scientific soundness, mainly towards nomenclature and interaction features [3]. The identified techniques and their interaction aspects then were normalized and classified into a concept matrix (addressing RQ1 and RQ2) based on the classification of the base article's typology (Figure 1). This way, the matrix facilitates the identification of any deviation(s) from the base article and addresses the MRQ. Comparative studies that included two or more locomotion techniques were tabulated in a respective number of rows [3]. Table 1 provides the literature review's concept matrix.

3. Results

The literature review documented 80 instances of 10 locomotion techniques in the 42 reviewed articles (Table 1). The walking-in-place locomotion technique was the most utilized (17 instances), followed by the controller/joystick-enabled locomotion technique (15 instances). The documented VR locomotion techniques and their numbers of instances are visualized in Figure 3 and answer RQ1. Their descriptions, based on their features and characteristics, are covered in Section 3.1 of [3], except for the gaze-based technique, which features users having their eye movements tracked by HMD-integrated, eye-tracking technologies (e.g., infrared lights and cameras) to control navigation [22].

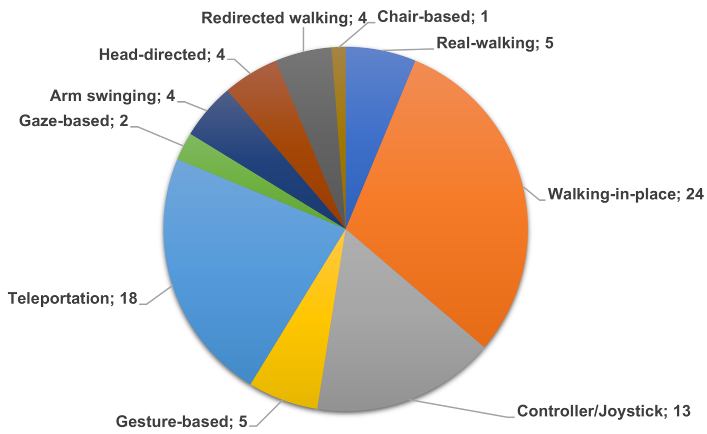

Figure 3. The number of instances of the 10 locomotion techniques, as documented from the 42 reviewed articles.

By classifying the documented VR locomotion techniques' interaction aspects based on the base article's typology, thereby answering RQ2, it became obvious that certain locomotion techniques (highlighted in a red font in Table 1, cf. [23,24]) and their VR locomotion types were not covered by the typology, thereby answering the MRQ. All these locomotion techniques featured teleportation, but their interaction type was physical and not artificial, as per the base article's typology (Figure 1).

Table 1. The reviewed techniques and their interaction aspects, classified into a concept matrix based on the proposed typology of Boletsis [3]. Techniques that are not covered by the typology are highlighted in red.

Article	**VR Locomotion Technique**										**Interaction Type**		**VR Motion Type**		**VR Interaction Space**		**VR Locomotion Type**			
	Controller/Joystick	**Walking-in-Place**	**Teleportation**	**Redirected Walking**	**Head-Directed**	**Gesture-Based**	**Real-Walking**	**Arm swinging**	**Chair-Based**	**Gaze-Based**	**Physical**	**Artificial**	**Continuous**	**Non-Continuous**	**Open**	**Limited**	**Motion-Based**	**Roomscale-Based**	**Controller-Based**	**Teleportation-Based**
Shimizu and Nakajima [25]	X											X	X		X				X	
Liu et al. [23]						X					X		X		X		X			
		X									X		X		X		X			
			X								X			X	X		?	?	?	?
Brument et al. [26]				X							X		X		X		X			
Kim et al. [9]		X									X		X		X		X			
		X									X		X		X		X			
	X											X	X		X				X	
			X									X		X	X					X
Freiwald et al. [27]			X									X		X	X					X
	X											X	X		X				X	
Dresel and Jochems [28]					X							X	X		X				X	
			X									X		X	X					X
Xing and Saunders [29]						X					X		X		X		X			
Mousas et al. [30]							X				X		X			X		X		
		X									X		X		X		X			
		X									X		X		X		X			
	X											X	X		X				X	
Keung et al. [31]		X									X		X		X		X			
Oumard et al. [32]	X											X	X		X				X	
Adhanom et al. [33]	X											X	X		X				X	
Arrighi et al. [34]			X									X		X	X					X
			X									X		X	X					X
Motyka et al. [35]		X									X		X		X		X			
Weissker and Froehlich [36]			X									X		X	X					X
Schäfer et al. [24]			X								X			X	X		?	?	?	?
			X								X			X	X		?	?	?	?
			X								X			X	X		?	?	?	?
			X								X			X	X		?	?	?	?
Englmeier et al. [37]			X									X		X	X					X
Ke and Zhu [38]		X									X		X		X		X			
		X									X		X		X		X			
		X									X		X		X		X			
Gao et al. [39]								X			X		X		X		X			
					X							X	X		X				X	
						X					X		X		X		X			
						X					X		X		X		X			
Nie and Rosenberg [40]				X							X		X		X		X			
Stein [22]										X	X		X		X		X			

Table 1. *Cont.*

Article	VR Locomotion Technique										Interaction Type		VR Motion Type		VR Interaction Space		VR Locomotion Type			
	Controller/Joystick	Walking-in-Place	Teleportation	Redirected Walking	Head-Directed	Gesture-Based	Real-Walking	Arm swinging	Chair-Based	Gaze-Based	Physical	Artificial	Continuous	Non-Continuous	Open	Limited	Motion-Based	Roomscale-Based	Controller-Based	Teleportation-Based
Cannavò et al. [41]								X			X		X		X		X			
		X									X		X		X		X			
		X									X		X		X		X			
	X											X	X		X				X	
Zhang et al. [42]		X									X		X		X		X			
Sun [43]				X							X		X		X		X			
Khundam [44]	X											X	X		X				X	
								X			X		X		X		X			
			X									X		X	X					X
Tastan et al. [45]			X									X		X	X					X
Otaran and Farkhatdinov [46]		X									X		X		X		X			
Kim and Xiong [47]		X									X		X		X		X			
Mittal et al. [48]				X							X		X		X		X			
de Oliveira et al. [49]							X				X		X			X		X		
Prithul et al. [50]					X							X	X		X				X	
	X											X	X		X				X	
Kim et al. [51]		X									X		X		X		X			
		X									X		X		X		X			
		X									X		X		X		X			
Khundam and Nöel [52]								X			X		X		X		X			
						X					X		X		X		X			
Wehden et al. [11]	X											X	X		X				X	
		X									X		X		X		X			
Awada et al. [53]	X											X	X		X				X	
		X									X		X		X		X			
Taylor and Cinelli [54]							X				X		X			X		X		
Buttussi and Chittaro [55]	X											X	X		X				X	
			X									X		X	X					X
									X			X	X		X				X	
Mayor et al. [56]					X							X	X		X				X	
	X											X	X		X				X	
			X									X		X	X					X
							X				X		X			X		X		
Schnack et al. [57]							X				X		X			X		X		
			X									X		X	X					X
Cherni et al. [58]		X									X		X		X		X			
Atkins et al. [59]			X									X		X	X					X
Chojecki et al. [60]		X									X		X		X		X			
		X									X		X		X		X			
		X									X		X		X		X			
Drewes et al. [61]										X	X		X		X		X			

4. Discussion

In this section, the review's results are discussed mainly by using the base article [3] as a point of reference to establish research continuity and simultaneously approach the goal of generalizing the elicited results. Naturally, other related articles were used in the results' analysis as well.

This discussion focuses on an examination of the typology's consistency and a new VR locomotion type that leads to an updated version of the typology (Section 4.3). Moreover, some observations can be made regarding the VR locomotion field's current status concerning expressed research interest (Section 4.1) and prevalent techniques (Section 4.2). The study's limitations also are discussed (Section 4.4).

4.1. Research Interest for VR Locomotion

A main observation from the literature review's results is that the search query for 2021 that was conducted elicited more reviewed articles and instances of VR locomotion techniques than the base article [3], which covered four years (2014–2017). Both articles used the same literature search strategy, adjusted for different years, as well as the same exclusion/inclusion criteria for the review.

In this article, the search elicited 61 articles, with their screening process eventually yielding 42 reviewed articles after a backward referencing search, documenting 80 instances of 10 locomotion techniques. In the base article by Boletsis [3], the search elicited 92 articles, with the screening process yielding 36 articles after a backward referencing search. Ultimately, 73 instances of 11 locomotion techniques were documented.

Simultaneously, a similar set of VR locomotion techniques was documented herein compared with the base article. This article contains no instances of reorientation and human joystick techniques, as in [3], but one gaze-based technique instance was found [22].

The comparison of the quantitative literature review's results for the two time periods covered in the two articles (2014–2017 vs. 2021) may attest to a growing research interest in VR locomotion over time. Research is highly active in this field, with researchers trying to address questions around usability and user experience of various existing techniques, re-examining updated VR locomotion techniques (e.g., gaze-based) in a new light, or developing new techniques. This also may suggest that when researching VR locomotion techniques, no definitive/static answer exists for a related research question because the experiential qualities that these techniques possess can be connected closely to and affected by their hardware, while VR and HMD hardware constantly is upgraded and improved.

4.2. Prevalent VR Locomotion Techniques

This study's literature review confirmed that the prevalent VR locomotion techniques are the walking-in-place (WIP), teleportation, and controller/joystick-based techniques, corresponding with related literature [62].

Walking-in-place (WIP) is still a prevalent VR locomotion technique (corresponding with the results from [3]). When looking more closely into the studies using WIP, a considerable number of them used treadmills for motion performance [11,31,35,41,53,58], which may suggest a need for "a more explicit focus on the perceived naturalness of WIP techniques; i.e., the degree to which WIP locomotion feels like real walking" [63]. Achieving higher levels of immersion may be the goal here, and more work on that topic, theoretical or technical, could be a promising research direction.

As for teleportation, in the base article [3], the following remarks were made: "...the VR teleportation technique is not studied or utilized as much" and "...this represents a discovered gap that can be addressed by future studies on VR locomotion." Apparently, this gap was addressed since then, and based on this review's results, VR teleportation is implemented and studied at a high degree, presenting more instances even than the controller/joystick (Figure 3). The fact that new teleportation implementations have been taken place—e.g., foot gestured-based teleportation [23], hand gesture-based teleportation [24], world-in-miniature teleportation [37], and menu-style teleportation [34]–might suggest rising interest in the technique and its interaction metaphors.

4.3. Motion-Based Teleporting Type

So far, based on the base article's typology (Figure 1), teleportation techniques featured only the artificial interaction type. In the "Study Limitations" section of that article

(Section 4.4 of [3]), it has been noted that "... a VR locomotion technique can integrate two or more locomotion techniques to facilitate navigation. For instance, point and teleport [6] utilizes gesture-based interaction to point to where the user wants to go, and the main motion takes place through teleportation... In this review, the VR locomotion techniques that integrate elements from other techniques were analyzed based on their dominant interaction aspects. In the aforementioned example, point and teleport was categorized as a teleportation-based technique, despite its gesture-based interaction aspects."

The fact that 'hybrid" VR locomotion techniques have been developed that integrate two or more locomotion techniques to facilitate navigation poses a challenge when documenting VR locomotion techniques, which is addressed by distinguishing between dominant and secondary interaction aspects based on the techniques' descriptions in the respective studies. When this strategy was applied to teleportation techniques with motion-based characteristics in the base article, few examples of these techniques were found from the examined 2014-2017 period (cf. [6]). Therefore, no notable results on those techniques were elicited. However, based on the present literature review's results (Table 1), five instances of teleportation techniques are not covered by the typology of Boletsis [3] (highlighted with a red font in Table 1). These five instances appear in works by Liu et al. [23] and Schäfer et al. [24], featuring teleportation techniques with physical interaction type.

Upon further investigation, the literature review on teleportation techniques by Prithul et al. [64] provided a detailed list of related techniques and studies, confirming this review's findings. Indeed, several VR teleportation techniques were enabled through physical interaction, as this review's findings also suggest. VR teleportation techniques can be motion-based, e.g., gesture-based teleportation [23,24], gaze-based teleportation [65], and redirected teleportation [66]. These techniques "inherit" the respective non-teleporting techniques' descriptions (Section 3.1 of [3]), but differ based on their non-continuous VR motion.

Therefore, an update to the proposed typology of Boletsis [3] is necessary to reflect a new type: "motion-based teleporting." The VR locomotion techniques under this type utilize physical movement (e.g., using hands, feet, or eyes) to enable interaction, while supporting non-continuous motion (visual "jumps" [3]) in open VR spaces. This type features physical interaction mechanics compared with the one that has artificial interaction mechanics, now called "controller-based teleporting". The formulated nomenclature for the other VR locomotion types was used to name the new additions and differentiate between them. Figure 4 presents the typology's updated version with some examples of VR locomotion techniques. It is expected that several non-teleporting techniques can have teleporting equivalents (e.g., head-directed teleportation can be implemented, falling under the controller-based teleporting type).

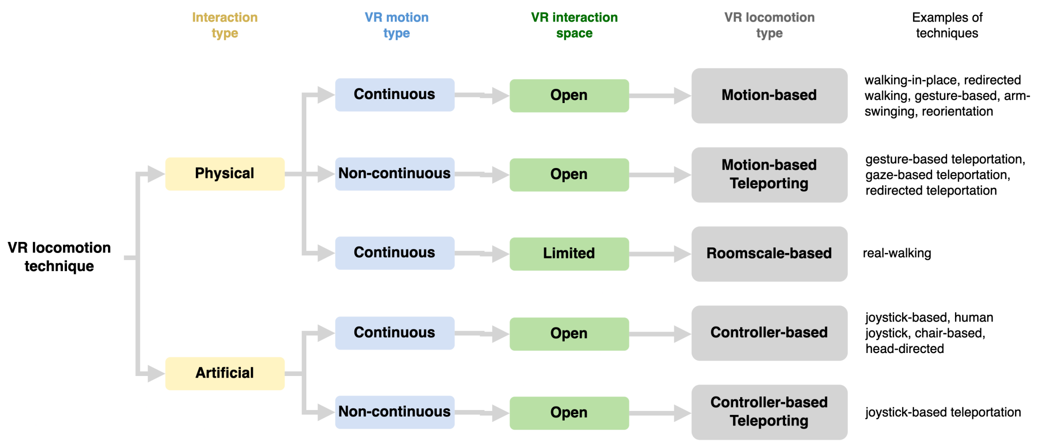

Figure 4. The updated typology of VR locomotion techniques.

4.4. Study Limitations

This study features certain compromises or assumptions that can be viewed as limitations.

- As stated above, a "hybrid" VR locomotion technique is possible, i.e., a technique integrating two or more other techniques. An example would be a joystick-based teleportation technique combined with real-walking. In this review, these techniques were documented based on the dominant VR locomotion technique, always according to the focus and descriptions in the respective reviewed articles.
- Considering that the literature review methodology of Boletsis [3] was utilized, the following limitation also was present: "The database query of the review is based on a predefined set of search terms. The defined search strategy conforms to the established procedures for systematic literature reviews [14]; however, with VR being a dynamic technical and research field, predefined sets of search terms might not be able to cover the number of works that utilize new or unestablished terminology."
- As in [3], the results of the reviewed, empirical studies were not included in the review; therefore, no information was available on the documented VR locomotion techniques' performance. Focusing on the techniques' performance was viewed as falling outside the scope of constructing a typology of VR locomotion techniques. The focus on the techniques' identification and the frequency of implementation in research were viewed as more relevant to the typology and to the study's RQs.

5. Conclusions

This study builds on the work of Boletsis [3], and the VR locomotion typology's consistency is investigated. A systematic literature review resulted in an analysis of the interaction attributes of 80 instances of VR locomotion techniques from 42 studies. They typology of Boletsis [3] could not cover teleportation-based techniques enabled by physical interaction; therefore, the typology was updated by introducing a new VR locomotion type: "motion-based teleporting." This typology, just like its predecessor, can help researchers and practitioners in the field position their work in the field while acquiring a high-level view of the state-of-the-art.

Future work could include: (i) conducting a systematic literature review covering the period between 2018 and the latest complete publication year, thus supplementing and extending the literature review of Boletsis [3]; and (ii) following up on advances regarding new or updated VR locomotion techniques to confirm the updated typology's consistency presented herein further.

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